

# Gondola for High Altitude Planetary Science (GHAPS) Telescope

## Secondary Mirror Positioning

### Hexapod Issues and Alternatives

Mark Wells

Senior Engineer, Advanced Materials Group, Dynetics Inc.

Huntsville, Alabama

#### Introduction

Active positioning of the GHAPS secondary telescope mirror is desired to correct for rigid body deflections due to temperature variations and gravity sag in the telescope structure that may impact optical performance. The current design concept for the secondary mirror mount uses a Commercial-Off-the-Shelf hexapod for mirror positioning and fine adjustment. The Hexapod specification states that motions as small as 0.1 microns along the optical axis and 2 microns perpendicular to the optical axis will cause optical aberrations that will require correction by repositioning the secondary mirror. In addition, the secondary mirror mount and positioning system must survive a 15g shock of parachute opening and landing during the instrument recovery operation. The secondary mirror positioning system must operate at a minimum specified temperature of -50C. The telescope operates in the IR and the secondary mirror mount and positioning device is in the metering path between the primary and secondary mirrors. I<sup>2</sup>R losses in positioning system actuator devices, which may cause heating of the positioning system and secondary mirror, must be minimized due to the previously mentioned alignment sensitivity and the viewing spectrum of interest.

The GHAPS project was cancelled on June 30, 2017. The purpose of this study is to address some of the issues identified with the hexapod secondary mirror positioning system and identify alternative approaches. This information may be used if the project is re-started at a later date.

#### Hexapod Issues

No commercial, off the shelf (COTS) hexapod system has been identified that will operate at -50C with a survival temperature of -75C at the time of this study. The current candidate, the PI H-824 hexapod, has a minimum operating temperature of -30C. The limiting factors identified were electronic component survival, Coefficient of Thermal Expansion (CTE) issues between the materials of construction for the hexapod actuator, and lubrication limitations at low temperature. COTS hexapod materials of construction are typically aluminum, stainless steels, brass, and polymers. The effective CTE of each hexapod element is the composite CTE of the actuator materials in series along the load path, which in the COTS case, can cause significant positioning error due to ambient temperature changes and self-

heating. The current placeholder for a COTS based hexapod, the PI H-824, uses a stepper motor driven screw and a rotary optical encoder for actuator element length control. Neither the individual actuator elements nor the hexapod system are preloaded in the current concept. Since the actuator element length is not measured directly by a linear position sensor, any lost motion in the drivetrain, the actuator element connections to the hexapod end plates, and CTE related position changes, is incorporated into the algorithm used to position the hexapod mounting structure in response to Wave Front Error based sensors.

The GHAPS secondary mirror positioning system requirement specifies the minimum increments of motion:

1. 10 micron in x and y (orthogonal to optical axis) with a 0.5 micron goal
2. 0.8 micron in z (piston or de-space) with a 0.1 micron goal
3. 1 arcsecond in tip and tilt with a 0.2 arcsec goal

The ranges of travels in the specification are  $\pm 12.5$  mm in x, y, and z as a goal, with greater than 0.1mm as the requirement. Range of travel for tip and tilt are  $\pm 0.5$  arcsecond (goal). It is understood that these requirements are based on minimal ground based alignment and positioning locking (using shims, epoxy, Stycast, etc.). If the Optical Tube Assembly is pre-aligned and locked, the secondary mirror range of motion requirements are reduced:

1. Z or Despace  $\pm 80$  microns
2. X and Y  $\pm 150$  microns
3. Tip and Tilt  $\pm 18$  arcseconds

Several design changes may be required to achieve a hexapod based approach which will meet both the positioning and environmental requirements. These are not all inclusive (i.e. direct measurement of hexapod actuator element length may not require an athermal actuator structure).

1. Direct measurement of hexapod actuator length between spherical bearing or flexure type attachment points to the end rings
2. Minimizing lost motion in the drive system.
3. Error correction in the drive system using a secondary actuator element, such as a piezo device, in series with the drive screw (fine and coarse adjustment). See Ref. 3.
4. Athermalization of the hexapod. Complete passive athermalization is not possible due to the varying length between the hexapod actuator drive screw and the drive nut at the motion take off point.
5. Alternate linear actuator drive methods such as piezoelectric, magnetostrictive, or voice coil type actuators.
6. Using the WFE sensor alone as the feedback position device. (i.e., move something until the error is minimized).

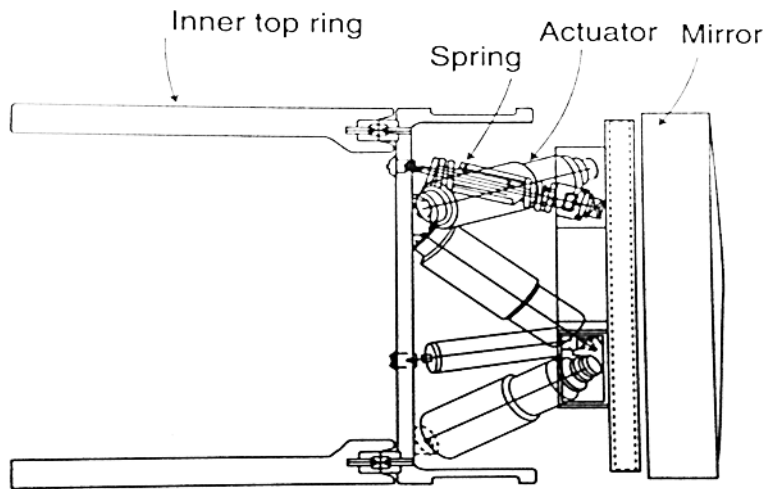
Several methods are available commercially for direct actuator length position measurement, but the limiting factor in most cases is the low temperature operating requirement of -50C. Linear optical

encoders (Heidenhain or equivalent) are capable of  $\pm 0.5$  micron resolution. Encoders of this type use Zerodur scales-on-Invar backing plate construction. The resolution provided is still not adequate for a 0.5 micron minimum increment goal, and the minimum temperature for commercial devices is 0C. Laser triangulation sensors (DMS devices) are limited to full range accuracy of 0.02% FS. They are repeatable down to 0.005 microns, but no commercial devices were found that will operate below 0C. Capacitance type sensors have very high resolution, typically of 1 part in  $10^5$  full-scale-range. However, no commercial devices were found with operating temperatures below 0C. LVDT type device resolution is dependent on the supporting electronics, but resolution down to 0.1 micron is possible. These have been operated down to 3 Kelvin, but temperature effects are typically 0.1%/degree C over the FS range.

“Inductosyn transducer” type devices are available for both rotary and linear measurements. These devices are similar to wire wound resolvers, but use printed circuit windings and monolithic construction. Devices are available with accuracies to 1 micron and resolution down to 0.025 micron for linear measurement, however size restrictions limit pole count, and accuracy is a function of the pole count of the device. Inductosyn devices have been used down to 10 degrees Kelvin. The monolithic construction results in a very rugged device and they are known for use in applications with high shock and impact loads. Inductosyn transducers have been used in space applications on the Hubble telescope, Space Shuttle, and military satellites. Further study is required in this area.

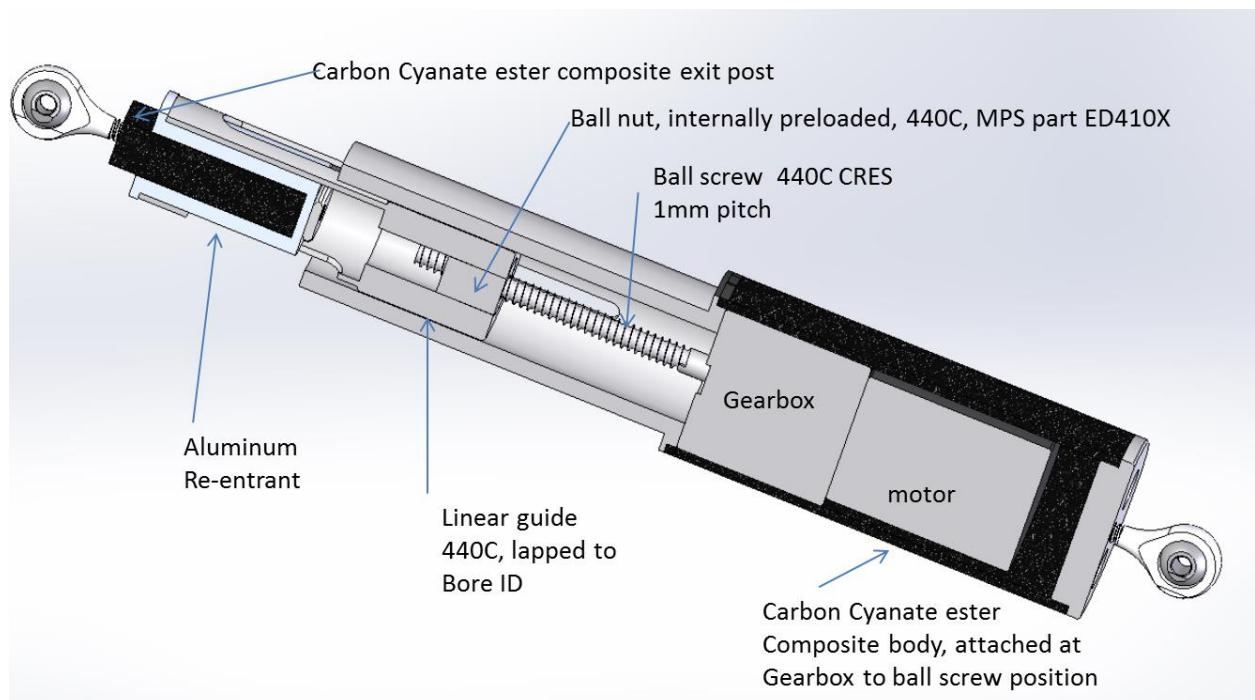
Direct measurement using interferometers is possible. Displacement measuring interferometers are available from Zygo that will meet position measurement requirements (order of magnitude greater than the minimum increment), but such a system would be difficult to implement due to the volume required and low temperature operation issues.

Lost motion or backlash in the actuator drive system may be improved by several methods. Lost motion or looseness in the actuator attachment points to the end plate structure may be improved by preloading the hexapod. An excellent example of this approach is the secondary positioning system used on the Subaru telescope mirror. This telescope also used a hexapod for secondary positioning. Three tensioning springs were used on the hexapod, one at the vertex of each actuator element attachment point. The tensioning springs keep the mirror cell pulled toward the hexapod base, eliminating play by loading both the actuator elements and attachment joints. See Ref. 1 and image below.



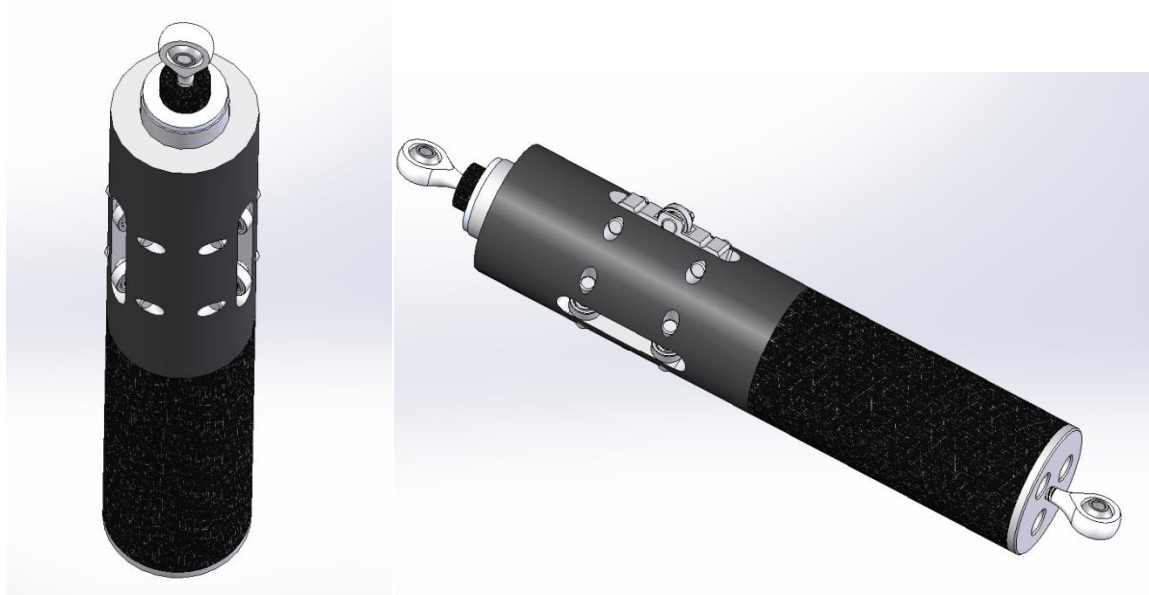
Lost motion may also be improved by using flexures or flexural pivots at the actuator end connections to the hexapod platform as opposed to spherical bearing type connections. If a rotary shaft encoder is used for position measurement of each hexapod element, backlash in the gear reduction system will show up as error, unless the desired position is always approached from one direction. Several methods are available for reducing or eliminating gear train error. One method is using the drive motor to drive through two planetary gear sets operating in parallel. The two gearsets couple back to a single drive pinion, which is used to drive the linear actuator screw. Lost motion is reduced by biasing the two gear sets against each other, using a spring or other method. Lost motion during directional changes is minimized. This approach is an unlikely candidate for the GHAPS system, due to the extra volume and mass required. An alternate approach considered for the purpose of this study is the use of a “Harmonic” type gear reducer. These devices are capable of zero backlash. A precursory study of available devices showed several candidate units that will fit the space requirements. The Harmonic drive company also offers a line of high precision linear actuators using harmonic drive reduction gearing. The company does not rate any of their devices for operation below -20C. The company was contacted regarding low temperature operation, but no explanation was offered. It is likely that a harmonic drive gearbox would require modification to operate reliably at -50C.

Athermalization (reducing temperature induced dimensional changes) may be approached, but not fully achieved for a hexapod linear actuator using passive athermalization techniques. Any actuator that uses a screw to convert rotary to linear motion will always have a variation in distance between the screw end and the drive nut. However, some degree of athermalization can be achieved by using re-entrant structures or a combination of both high and very low CTE materials in series to correct for dimensional changes of structure and components. Low CTE materials include Invar and some carbon composites. High CTE materials include aluminum alloys. A notional linear actuator was modeled in CAD and illustrations are shown below.



The linear actuator concept uses low CTE components in the load path and a re-entrant of aluminum to compensate for CTE related length changes of the drive screw and drive nut guide sleeve. The load transfer structure from the gearbox mounting plate, at the ball screw coupling, is fabricated from a low

CTE carbon-cyanate ester composite tube. The drive nut guide sleeve attaches to an aluminum re-entrant tube. The re-entrant is attached to a low CTE carbon-cyanate ester post, which attaches to the front actuator coupling, which for this illustration, is a spherical bearing rod end. As the ballscrew, drive nut guide sleeve and end fittings shrink in length as the actuator temperature decreases, the aluminum re-entrant also decreases in length, but compensating in the opposite direction of the decrease in length of the other components. The ball screw, ball nut and balls, and drive sleeve are fabricated from 440C CRES. Drive nut sleeve linear guidance is a potential problem with a large temperature range device. The nut guide sleeve in the above concept is OD lapped to fit the ID lapped bore of the guide tube with a tribological coating at the interface and depends on the assembly reaching thermal equilibrium for successful operation. Another possible solution linear guidance of the actuator output is a semi-kinematic V-guide using two sets of ball bearing guides, with one ball bearing being preloaded against the guide surface. This type of device has been used successfully in optical positioning in high altitude air-born optics. An illustration of this concept is show below:



A pin in slot device is used to prevent rotation of the nut in these concepts. Lubrication would be a combination of low temperature greases, such as Castrol Braycote 601EF (perfluorinated grease rated to -80C), and dry film lubricants (MoS<sub>2</sub>). The ball-screw shown in these illustrations is from MPS Microsystems.

Various piezo electric devices are available as linear drive actuators. These include “inchworm” linear motors, stick-slip inertia and ultrasonic motors, piezo-rotary motors using screw-nut assemblies for linear motion, and flexure based kinematic linkage piezo actuators. DSM Piezo in Franklin Tennessee was contacted about this application and low temperature operation of piezo type devices. The travel range of a piezo device decreases with temperature and special electrical contact bonding methods are required for low temperature operation. One of their linear actuators, DSM FPA-2000 was tested for an application at -50C. The stroke reduction from room temperature is approximately 28% of the total travel range. Another actuator they have tested is a 25 micron range actuator (at 20C) which a stroke of

10 microns at LN2 temperature (-195C). DSM does not offer an off-the-shelf solution for this application, but they believed they could use a current actuator developed for a commercial customer, the DSM parallel kinematic stage, as a foundation for a system meeting the GHAPS secondary mirror positioning requirements.

Janssen Precision Engineering in the Netherlands was contacted regarding a cryogenic hexapod system they offer as a commercial product. Unfortunately, this device did not have the capacity required by the GHAPS system, but the company also manufactures a number of cryogenic actuators and encoders using piezo electric devices that may have application for other types of mirror alignment devices.

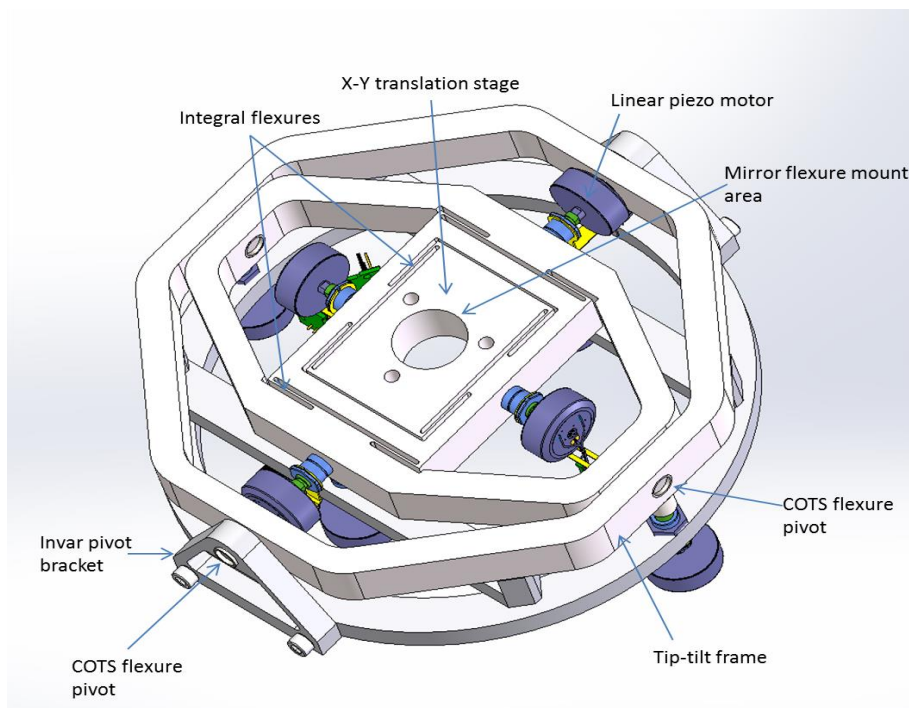
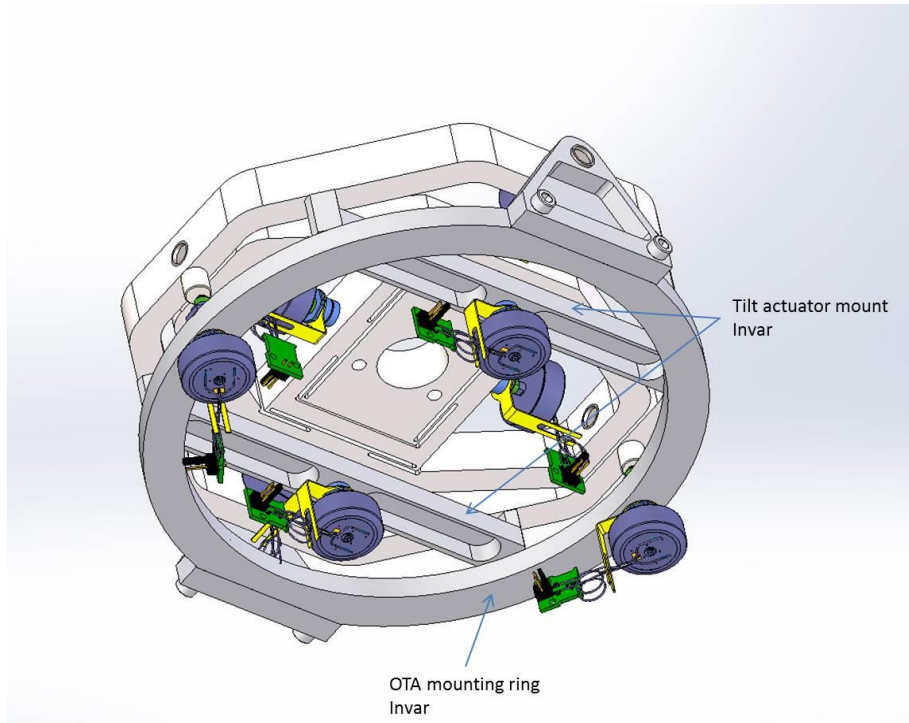
Both magnetostrictive and voice coil type actuators were considered. Magnetostrictive devices are capable of generating high forces (high force to actuator volume), very high inherent stiffness, and are capable of operating at cryogenic temperatures, but have significant  $I^2R$  losses. Ref. 2. Voice coil actuators also suffer from significant  $I^2R$  losses, have very low passive stiffness, and must be powered to maintain position. Ref. 3. Heating losses are considered detrimental to this telescope application. Power dissipation within the mirror adjustment system will affect the thermal emission of the secondary mirror.

#### Another Approach – a flexure based stage system

For small rotation angles of up to 6 degrees and small translation ranges from 1 to 2 mm, flexures have the advantage of no stick-slip behavior, very low friction and hysteresis, minimal or no lost motion, and they do not require lubrication. A flexure based concept was developed for this study. The concept presented provides x,y translation and tip-tilt adjustment of the secondary mirror. The concept requires permanent “coarse” pre-alignment of the OTA on the ground due to limited travel range, so the secondary mirror alignment system only corrects for smaller range adjustments due to residual deflection of the OTA structure due to temperature variations and gravity sag. The concept presented is based on using a COTS actuator device from Janssen Precision Engineering rated for cryogenic operation. The model number is CLA2601-COE. The device uses a piezo ceramic motor to rotate a spindle relative to a stationary nut, producing linear motion. The device has a 6mm travel range, a step size at 4K of 5 nm, a maximum driving force of 40N, and a translation velocity of 3 microns/second at 4K and 15 microns/second at 293K. The concept shown uses these devices in a push-push configuration on each axis, but a single actuator could be used with a biasing spring in place of one of the actuators. In a push-push configuration, one actuator moves the stage in one direction only, and is unloaded when the opposing actuator moves in the opposite direction. A push-pull configuration may also be possible, but would require some degree of compliance in the structure between the two actuators to prevent jamming due to variation or non-linearity in stroke.

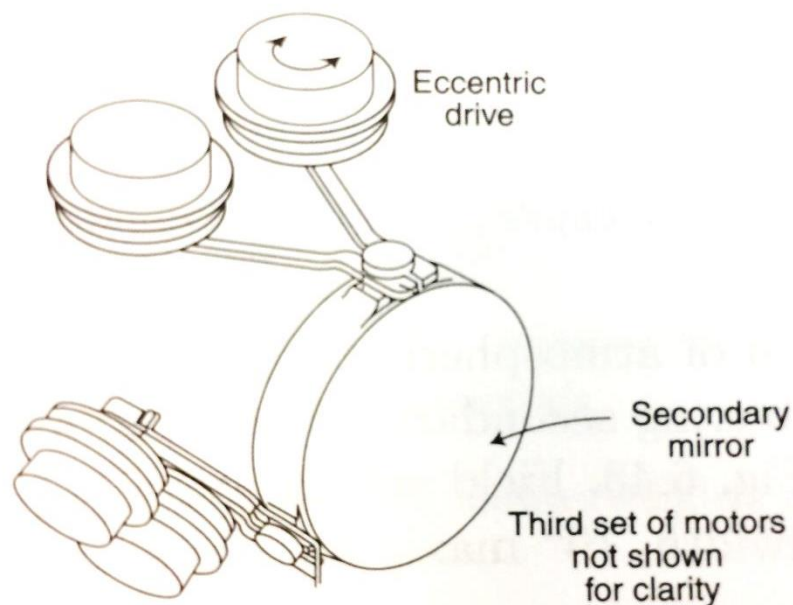
The concept is approximately 8 inches (204mm) in diameter and 3 inches (76mm) in height. The assembly weighs 1.7kg. The x-y flexure assembly and gimbal are 6Al4V titanium. Titanium has a high yield strength to modulus ratio, which is desirable in flexure design. This concept lends itself to wire EDM fabrication methods. The x-y actuator mounts are structurally isolated from each other, preventing cross coupling issues. The flexure beams for the x-y translation stage are notional, only a very

preliminary analysis has been performed. The tip-tilt gimbal flexure pivots are commercially available part number 5012-600 from Riverhawk. The base ring, tilt actuator mounts, and flexure brackets are Invar, however low CTE carbon composite components could be substituted for reduced mass. The concept presented does not provide z axis or piston translation for focusing.





As previously stated, this concept presented in this brief study is to demonstrate that an alternate approach to a hexapod is possible using COTS actuators and a flexure based design. Further work would likely result in better approaches and a more optimal structure. Other alternate approaches that may be considered are eccentric drive six link positioners like those employed in the Hubble telescope secondary mount. This device operates in a similar fashion to a hexapod system, but using limited range rotary actuators to achieve tip-tilt- and translation of the secondary mirror mount. An illustration is shown below.



## Conclusion

A Hexapod mount provides a very optimal approach for secondary mirror positioning for the GHAPS telescope in terms of positioning flexibility and mass. The deficiency lies in the lack of COTS systems which will meet the minimum positioning system increments at -50C, without adding a significant heat load to the secondary mirror. Meeting these requirements will likely require a custom actuator device, with a corresponding impact on project cost and schedule, should the project resume. Alternate approaches, using flexure based position guidance with linear piezoelectric actuators are feasible, but also require significant engineering time for development and optimization. In conclusion, no COTS solution for this design problem was found within the limited scope of this study task.

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